

# Transverse structure of strong interactions at LHC: From diffraction to new particle production \*

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We discuss the global structure of  $pp$  events at LHC with hard processes (particle production in two-parton collisions) on the basis of the transverse spatial characteristics of the partonic initial state. Studies of hard exclusive processes in  $ep$  scattering have shown that the transverse area occupied by partons with  $x \geq 10^{-2}$  is much smaller than the size of the nucleon as it appears in generic inelastic  $pp$  collisions at high energies (“two-scale picture”). We show that this is consistent with the observation that the elastic  $pp$  amplitude at the Tevatron energy is close to the black body limit at small impact parameters. Our picture implies that inclusive heavy particle production (Higgs, SUSY) happens only in central  $pp$  collisions. At LHC energies, the final state characteristics of such events are strongly influenced by the approach to the black body limit, and thus may differ substantially from what one expects based on the extrapolation of Tevatron results. Our two-scale picture also allows us to analyze several types of hard diffractive processes observable at LHC: *i*) Diffractive proton dissociation into three jets, which probes small-size configurations in the proton wave function; *ii*) exclusive diffractive Higgs production, in which we estimate the rapidity gap survival probability; *iii*) inclusive diffractive processes.

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## I. INTRODUCTION

Hard processes, such as the production of high- $p_{\perp}$  dijets or heavy particles, provide a chance to apply QCD to the theory of  $pp/\bar{p}p$  collisions at high energies. The dominant mechanism for these processes are collisions of two partons. Thanks to QCD factorization theorems, the cross section for these processes can be represented as the product of the hard partonic cross section, calculable in perturbative QCD, and functions describing the distribution of partons in the initial state. To calculate the total cross section for hard processes requires knowledge only of the distributions of partons with respect to longitudinal momentum, which are known from inclusive DIS and related experiments. A much more challenging problem is to describe the properties of the hadronic final state in events with hard processes, *e.g.*, the average hadron multiplicities in events with heavy particle production, or the probability for hard diffractive events with large rapidity gaps. These problems require knowledge also of the transverse spatial distribution of partons in the initial state (including its dependence on flavor and spin), as well as parton-parton correlations.

The transverse spatial distribution of partons in the proton is probed in hard exclusive electro/photoproduction processes, such as the electroproduction of vector mesons ( $\rho, \phi$ ) or real photons (deeply virtual Compton scattering), or the photoproduction of heavy quarkonia ( $J/\psi, \psi', \Upsilon$ ), by measuring the  $t$ -dependence of the differential cross sections. Such measurements at FNAL and HERA have provided a rather detailed picture of the transverse spatial distribution of gluons down to momentum fractions of the order  $x \sim 10^{-4}$ . In particular, these results have shown that the transverse area occupied by partons with  $x \geq 10^{-2}$  is *much smaller* than the transverse size of the proton in generic inelastic  $pp/\bar{p}p$  collisions at high energies. Since the latter size rises rapidly with energy, the difference between the two transverse areas, which is already significant at Tevatron energies, is expected to become even more pronounced at LHC. One is dealing with an “onion-like” transverse structure of the nucleon, as depicted in Fig. 1.

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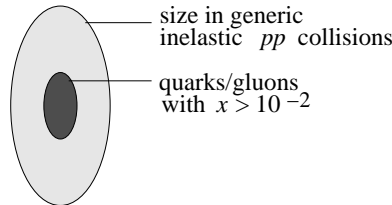


Figure 1: The “onion-like” transverse structure of the nucleon in high-energy  $pp$  collisions.

This two-scale picture is the key to understanding the properties of the hadronic final state in  $pp$  events with hard processes at LHC.

First, the two-scale picture of Fig. 1 implies a classification of  $pp/\bar{p}p$  events in “central” (areas of large- $x$  partons overlap) and “generic” ones (areas of large- $x$  partons need not overlap). The “generic” collisions give the dominant contribution to the overall inelastic cross section. Hard processes such as heavy particle production will practically only happen in “central” collisions [1]. A new phenomenon expected at LHC is the approach to the “black body limit” of strong interactions due to the interactions of large- $x$  partons with the strong small- $x$  gluon field in the other proton. This has profound consequences for the pattern of hadron production, in particular in the forward/backward rapidity region. These strong interaction effects need to be understood in order to reliably identify signals due to new particles.

Second, the two-scale picture of the transverse structure of the nucleon can be applied to diffractive processes in  $pp$  scattering, in which the particles produced in the hard process are separated from the rest by rapidity gaps. One example is the diffractive dissociation of one of the protons into three jets,  $p + p \rightarrow 3 \text{ jets} + (\text{gap}) + p$ . This process proceeds from small-size configurations in the dissociating proton, and is the analogue of the diffractive two-jet dissociation of pions in  $\pi A$  collisions. In particular, measurements of such processes will allow to investigate whether the fast increase with energy of the gluon density in the nucleon, predicted by DGLAP evolution in QCD and observed at HERA, will slow down as suggested by various resummation approaches [2]. Another example is the exclusive diffractive production of heavy particles,  $p + p \rightarrow p + (\text{gap}) + H + (\text{gap}) + p$ , which is being discussed as a candidate for the Higgs search at LHC [3]. Here, the requirement that soft interactions between the spectator systems preserve the rapidity gaps results in a suppression of the cross section compared to the non-diffractive case, which can be estimated using information from  $pp$  elastic scattering. The same applies to inclusive diffractive processes,  $p + p \rightarrow p + (\text{gap}) + 2 \text{ jets} + X$  or  $p + (\text{gap}) + 2 \text{ jets} + X + (\text{gap}) + p$ .

## II. TRANSVERSE STRUCTURE OF THE NUCLEON IN HIGH-ENERGY PROCESSES

Information about the spatial distribution of partons in the transverse plane comes from studies of hard exclusive processes in  $ep$  scattering, in particular the electroproduction of light vector mesons ( $\rho, \phi$ ) at large  $Q^2$ , and the photoproduction of heavy quarkonia ( $J/\psi, \psi', \Upsilon$ ). These processes probe the generalized parton distributions in the nucleon. The extensive data on vector meson production at HERA (for a review, see Ref.[4]) support the dominance of the partonic mechanism. In particular, they confirm a qualitative prediction of QCD factorization — the convergence of the  $t$ -slope of  $\rho$  meson electroproduction at large  $Q^2$  to the slope of  $J/\psi$  photo/electroproduction [5], see Fig. 2. Numerical calculations, accounting for the finite transverse size of the wave function of the produced vector meson, explain the key features of the high- $Q^2$  data [7]. The  $t$ -dependence of the cross section for  $J/\psi$  photo/electroproduction is given (up to small corrections) by the square of the “two-gluon form factor” of the nucleon [8],

$$\frac{d\sigma^{\gamma^* p \rightarrow J/\psi p}}{dt}(t) \propto [F_g(x, t)]^2, \quad x \sim M_{\bar{c}c}^2/W^2. \quad (1)$$

The two-dimensional Fourier transform of this function,

$$F_g(x, \rho) \equiv \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-i(\Delta_\perp \rho)} F_g(x, t) \quad (t = -\Delta_\perp^2), \quad (2)$$

describes the spatial distribution of gluons with momentum fraction  $x$  in the transverse plane [the distribution is normalized as  $\int d^2 \rho F_g(x, \rho) = 1$ ]. Thus, one can map the distribution of gluons in the transverse plane from the measured  $t$ -dependence of the cross section.

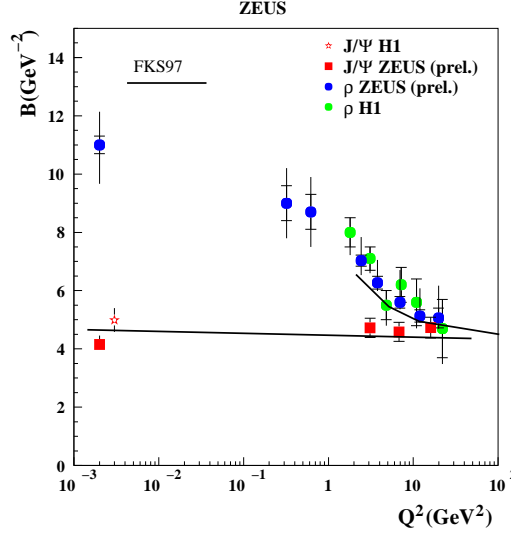


Figure 2: Convergence of the  $t$ -slopes of  $\rho$  and  $J/\psi$  electroproduction at large  $Q^2$ . The compilation of the data is from Ref. [6]. The solid curves are the theoretical predictions of Ref. [7] for the  $Q^2$  dependence of the  $t$ -slopes.

A simple phenomenological parameterization of the two-gluon form factor of the nucleon, including its variation with  $x$ , is the dipole form [1, 8]

$$F_g(x, t) = (1 - t/m_g^2)^{-2}, \quad m_g^2 \equiv m_g^2(x, Q^2). \quad (3)$$

This form is motivated by the expectation that at  $x \geq 0.1$ , where the contribution of the nucleon's pion cloud is suppressed, the two-gluon form factor should follow the axial form factor of the nucleon ( $m_g^2 \approx m_A^2 = 1.1 \text{ GeV}^2$ ). It describes well the  $t$ -slopes of  $J/\psi$  photoproduction measured in a number of fixed-target experiments [8]. The experimentally observed increase of the slope between  $x \sim 0.1$  and  $x \sim 0.01$  can be explained by contributions of the nucleon's pion cloud to the gluon distribution at transverse distances  $\rho \sim 1/(2M_\pi)$  [9]. This effect, as well as the subsequent slow increase of the slope at smaller  $x$ , and the small effects of DGLAP evolution, are incorporated by way of an  $x$ - and  $Q^2$ -dependence of the dipole mass parameter, see Refs. [1, 10] for details. The Fourier transform of Eq. (3), *cf.* Eq. (2), defines our parametrization of the transverse spatial distribution of gluons.

A crucial observation is that the transverse area occupied by partons with significant momentum fraction,  $x \geq 10^{-2}$ , is much smaller than the size of the nucleon as it appears in generic inelastic  $pp$  collisions at high energies. This can qualitatively be understood in Gribov's picture of the partonic wave function of the nucleon, which allows for a unified description of electromagnetic and strong interactions at high energies [11]. In this picture, the  $pp$  cross section is dominated by collisions of “soft” partons (very small  $x$ ), which are the result of successive decays of the “hard” partons at large  $x$ . This decay process has the character of a random walk in the transverse plane (“Gribov diffusion”). Each decay process results in a shift of the transverse position inversely proportional to the transverse momentum in the decay vertex,  $\sim 1/k_\perp$ . Due to the randomness of the emissions, and the constant degrading of the longitudinal momentum, one finds that  $n$  successive decays result in an overall increase of the transverse area of

$$R^2(n) \propto \frac{n}{k_\perp^2} \propto \frac{\ln(x_0/x)}{k_\perp^2}. \quad (4)$$

The transverse area occupied by soft partons thus grows linearly with  $\ln s$ . For hard partons the growth of the transverse area with the collision energy is much weaker, due to the smaller scale of the random shifts in impact parameter space. In addition, the transverse area occupied by the hard partons at large  $x$  is already small. This leads to the appearance of two widely separated transverse area scales in  $pp$  collisions at high energies (see Fig. 1) — a small transverse area occupied by hard partons, and a much larger area occupied by soft partons.

In order to quantify the transverse size of the nucleon in inelastic  $pp$  collisions one can use phenomenological parameterizations of the  $pp$  elastic scattering amplitude at high energies in the impact parameter representation,

$$\Gamma^{pp}(s, b) \equiv \frac{4\pi}{is} \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i(\Delta_\perp b)} A^{pp}(s, t) \quad (t = -\Delta_\perp^2). \quad (5)$$

By unitarity, the probability for an inelastic collision at a given impact parameter,  $b$ , is related to  $\Gamma^{pp}(s, b)$  as

$$2 \text{Re} \Gamma^{pp}(s, b) - |\Gamma^{pp}(s, b)|^2. \quad (6)$$

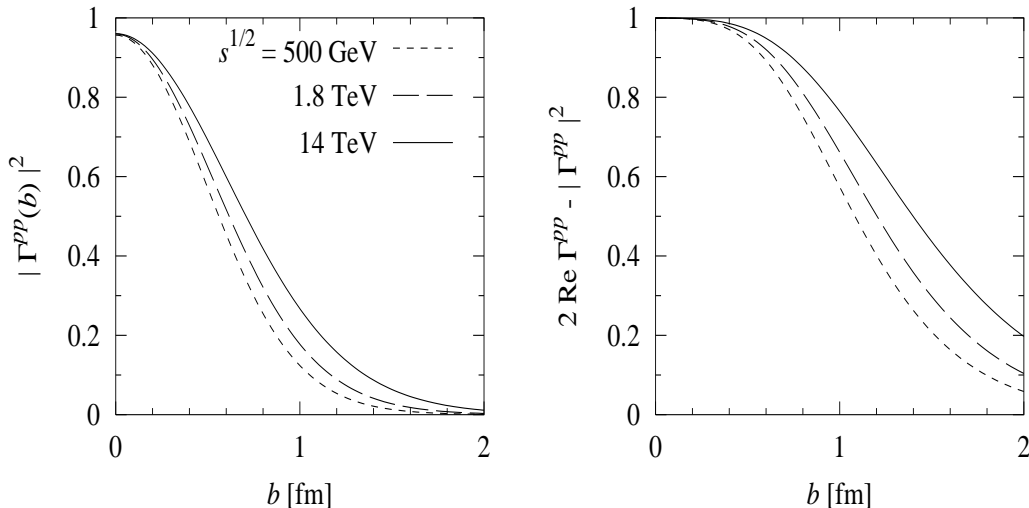


Figure 3: Left panel: Modulus squared of the  $pp$  elastic amplitude in impact parameter representation,  $\Gamma^{pp}(b)$ , Eq. (5). Right panel: The probability for inelastic interaction at a given impact parameter, Eq. (6).

Fig. 3 shows  $|\Gamma^{pp}(s, b)|^2$  and the probability (6) obtained from the parameterization of Ref. [12]. One clearly sees how the radius of strong interactions increases with the collision energy. In Gribov's picture, this reflects the increase of the transverse area occupied by the soft partons.

### III. HARD INTERACTIONS AND THE “BLACK BODY LIMIT” IN ELASTIC $pp$ SCATTERING

Parameterizations of the  $pp$  elastic amplitude indicate that at high energies the strength of the interaction at small impact parameters approaches the “black body limit”,  $\Gamma^{pp} \approx 1$ , corresponding to unit probability for inelastic interactions, see Fig. 3. A rough estimate of the maximum impact parameter for which the interaction remains black can be made in the single Pomeron exchange model of the total cross section. The minimum invariant energy for which  $\Gamma^{pp}(b=0) \approx 1$  is approximately the Tevatron energy,  $s_T \approx (2 \text{ TeV})^2$ . For  $s > s_T$ , the total cross section then grows as  $\sigma_{\text{tot}} \propto (s/s_T)^{\alpha_P(0)-1}$ , while the  $t$ -slope of the elastic cross section grows as  $B_P = B_T + 2\alpha' \ln(s/s_T)$ . One finds that  $\Gamma^{pp}$  reaches unity at

$$b_F^2 \approx [\alpha_P(0) - 1] \ln(s/s_T) B_P. \quad (7)$$

This corresponds to the universal Froissart limiting behavior of hadronic total cross sections (same for all hadrons and nuclei).

In QCD, the “blackening” of the  $pp$  interaction at small impact parameters could arise from hard as well as soft interactions. It is interesting to estimate the role of hard interactions in the approach to the black body limit within our two-scale picture of the transverse partonic structure of the nucleon. The analysis of Ref. [1] (see Section IV below) shows that in central  $pp$  collisions the leading quarks and gluons receive significant transverse momenta when passing through the gluon field of the other proton. For example, at Tevatron energies, quarks with  $x_1 \geq 0.2$  get on average transverse momenta  $> 1 \text{ GeV}/c$ , see Section V below. When a single leading quark gets a transverse momentum,  $p_\perp$ , the probability for the nucleon to remain intact is approximately given by the square of the nucleon form factor,  $F_N^2(p_\perp^2)$ , which is  $\leq 0.1$  for  $p_\perp > 1 \text{ GeV}/c$ , *i.e.*, very small. One may thus conclude that the probability of the survival averaged over  $p_\perp$  should be less than 1/2 (on average, half of the time the quark should receive a transverse momentum larger than the average transverse momentum,  $p_\perp > 1 \text{ GeV}/c$ ). Since there are six leading quarks (plus a number of leading gluons), the probability for the two protons to stay intact,  $|1 - \Gamma^{pp}(s, b)|^2$ , should go as a high power of the survival probability for the case of single parton removal, and thus be very small. This crude estimate shows that already at Tevatron energies  $|1 - \Gamma^{pp}(s, b=0)|^2$  should be close to zero due to hard interactions, which is consistent with phenomenological parameterizations of the  $pp$  elastic amplitude, see above. We conclude that hard interactions alone are sufficient to ensure “blackness” of the inelastic interactions at small impact parameters.

One can estimate the maximum impact parameter up to which hard interactions cause the  $pp$  interaction to be “black”. The probability for a leading parton with  $x_1 \sim 10^{-1}$  to experience a hard inelastic interaction increases with the collision energy at least as fast as corresponding to the increase of the gluon density in the other proton at

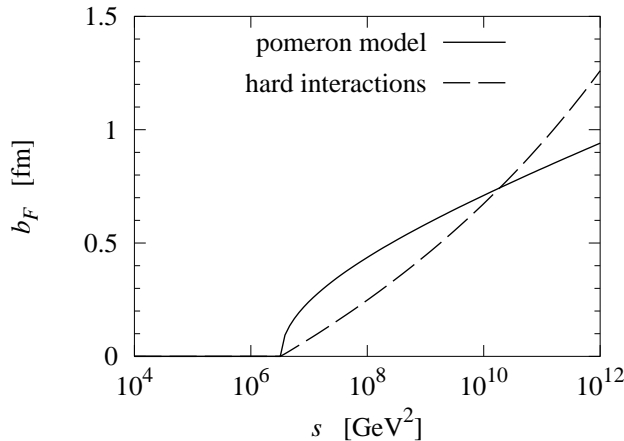


Figure 4: Energy dependence of the maximum impact parameter for “black”  $pp$  interactions,  $b_F$ . Solid line: Estimate based on the pomeron model, Eq. (7). Dashed line: Estimate based on hard interactions, Eq. 8.

$x_2 = 4p_\perp^2/(sx_1)$ , *cf.* Eq. (12) below. Since  $x_2 G_N(x_2, Q^2) \propto x_2^{-n_h}$  with  $n_h \geq 0.2$ , this implies that the probability should grow as  $s^{n_h}$  [25]. Our parametrization of the transverse spatial distribution of gluons, *cf.* Eq. 2, suggests that the gluon density decreases with the distance from the center of the nucleon approximately as  $\sim \exp[-m_g(x_2)\rho]$ . If one neglects the transverse spread of the large- $x_1$  partons as compared to that of the small- $x_2$  gluons one arrives at an estimate of the energy dependence of  $b_F$  as due to hard interactions [13],

$$b_F \approx \frac{n_h \ln(s/s_T)}{m_g(x_2)}, \quad (8)$$

with  $x_2$  as defined above. It is very encouraging that this estimate agrees well with that obtained above in the pomeron model, Eq. (7), see Fig. 4. This shows that our two-scale picture of the transverse structure of the nucleon — and the ensuing picture of hard and soft interactions — are self-consistent.

Measurements of elastic  $pp$  scattering at LHC will allow to investigate the onset of the black body limit in  $pp$  interactions. Such studies not only probe the structure of the nucleon periphery at very high energies, but also provide important constraints for models of inelastic interactions at smaller impact parameters.

#### IV. NEW PARTICLE PRODUCTION IN CENTRAL $pp$ COLLISIONS

The two-scale picture of the transverse structure of the nucleon, see Fig. 1 and Section II, implies a classification of  $pp/\bar{p}p$  events in “central” (areas of large- $x$  partons overlap) and “generic” ones (areas of large- $x$  partons need not overlap), see Fig. 5 [1]. Generic collisions give the dominant contribution to the overall inelastic cross section. Hard processes, such as heavy particle production at central rapidities, will practically only happen in central collisions.

To quantify the distinction between generic and central collisions, we estimate the distribution of both types of events over the  $pp$  impact parameters. For generic collisions, the distribution is determined by the  $b$ -dependent probability of inelastic interaction, Eq. (6), obtained via unitarity from the elastic  $pp$  amplitude in the impact parameter representation. We define a normalized  $b$ -distribution as

$$P_{\text{in}}(s, b) = \frac{2\text{Re } \Gamma^{pp}(s, b) - |\Gamma^{pp}(s, b)|^2}{\sigma_{\text{in}}(s)}, \quad (9)$$

where  $\sigma_{\text{in}}(s)$  is the inelastic cross section, which is given by the integral  $\int d^2b$  of the expression in the numerator. For collisions with a hard process, on the other hand, the  $b$ -distribution is determined by the overlap integral of the distribution of hard partons in the two colliding protons (see Fig. 5),

$$P_2(b) \equiv \int d^2\rho_1 \int d^2\rho_2 \delta^{(2)}(\mathbf{b} - \boldsymbol{\rho}_1 + \boldsymbol{\rho}_2) F_g(x_1, \rho_1) F_g(x_2, \rho_2). \quad (10)$$

Numerical estimates can be performed with our parametrization of the transverse spatial distribution of hard gluons, Eq. (3), which takes into account the change of the distribution with  $x$  and the scale of the hard process. The two

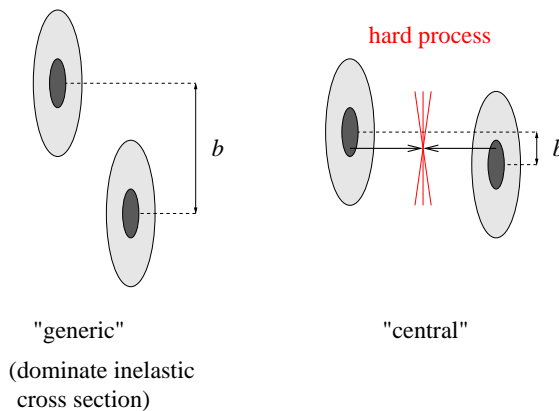


Figure 5: Classification of  $pp$  events at high energies.

$b$ -distributions are compared in Fig. 6 for Tevatron and LHC energies. For the hard process we have taken the production of a dijet with  $q_{\perp} = 25$  GeV; in the case of Higgs production at LHC the distribution  $P_2(b)$  would be even narrower. The results clearly show that events with hard processes have a much narrower impact parameter distribution than generic inelastic events.

One expects that at LHC energies the rate of production of two pairs of jets will be very high. It is interesting to consider the  $b$ -distribution also for the production of two dijets in two binary parton-parton collisions. Neglecting possible correlations between the partons in the transverse plane it is given by

$$P_4(b) \equiv \frac{[P_2(b)]^2}{\int d^2b [P_2(b)]^2}. \quad (11)$$

Fig. 6 shows that this distribution is significantly narrower than  $P_2$ , *i.e.*, the requirement of two hard processes results in a further reduction of effective impact parameters. Note that there are indications of significant correlations in the transverse positions of two partons, which would effectively reduce the difference between the  $b$ -distribution in double dijet and single dijet events; see Refs. [1, 14] for details.

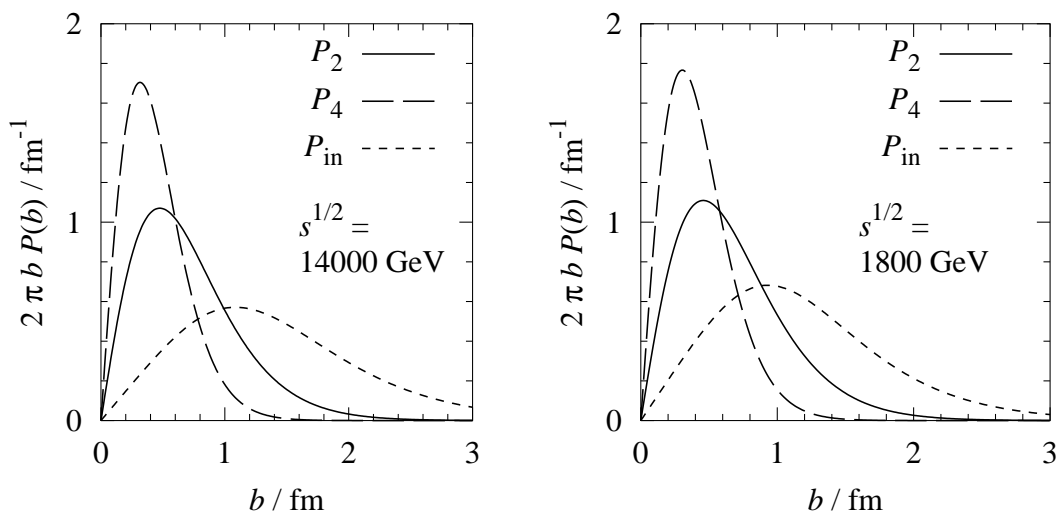


Figure 6: *Solid lines:*  $b$ -distributions for events with hard dijet production,  $P_2(b)$ , with  $q_{\perp} = 25$  GeV. *Long-dashed line:*  $b$ -distribution for double dijet events,  $P_4(b)$ . *Short-dashed line:*  $b$ -distribution for generic inelastic collisions, obtained from the parameterization of the elastic  $pp$  amplitude of Islam *et al.* [12]. The plots show the “radial” distributions in the impact parameter plane,  $2\pi b P(b)$ .

## V. ONSET OF THE BLACK BODY LIMIT IN CENTRAL $pp$ COLLISIONS

A new phenomenon encountered in central  $pp$  collisions at LHC energies is that the interaction of leading partons in one proton with the gluon field in the other proton approaches the maximum strength allowed by  $s$ -channel unitarity (“black body limit”). As a result, the structure of the final state in central  $pp$  collisions differs in many respects — leading particle spectra, multiplicities of soft hadrons at central rapidities, long range correlations — from that of generic inelastic events.

Generally, in particle production in hard parton–parton collisions, a parton with momentum fraction  $x_1$  and transverse momentum  $p_\perp$  in one proton resolves partons in the other proton with momentum fraction

$$x_2 = \frac{4p_\perp^2}{x_1 s}. \quad (12)$$

In leading particle production at LHC ( $\sqrt{s} = 14$  TeV) a leading parton with  $x_1 \sim 10^{-1}$  and significant transverse momentum,  $p_\perp \sim 2$  GeV/ $c$ , resolves partons with  $x_2 \sim 10^{-6}$  in the other proton. In this situation the gluon density in this proton is so large that “taming” effects cannot be neglected; for a review and references see Ref. [15]. The leading parton can be thought of as propagating through a high-density “gluon medium”, or, equivalently, a strong gluon field, in the other proton, see Fig. 7. The interaction of the leading parton with the other proton approaches the “black body limit”, characterized by a near unity probability for inelastic scattering. In fact, in  $pp$  collisions at LHC the leading partons propagate through gluon fields with a strength comparable to that in central  $pA$  collisions at similar energies.

The “black” interactions are experienced by leading partons with transverse momenta up to a certain critical value,  $p_{\perp, \text{BBL}}$  [the  $x_2$  of the gluon density probed is proportional to  $p_\perp^2$ , *cf.* Eq. (12)]. Conversely, this means that low- $p_\perp$  leading partons will on average acquire transverse momenta of the order  $p_{\perp, \text{BBL}}$  through their interactions with the strong gluon field, which results in certain modifications of the pattern or particle production at forward/backward rapidities, see Section VI below.[26] We have estimated the critical transverse momentum,  $p_{\perp, \text{BBL}}$ , using phenomenological parametrizations of the gluon density at small  $x_2$ , and our parametrization of the transverse spatial distribution of gluons, Eq. (3) [1]. For simplicity, we considered the scattering of a small color-singlet dipole off the “target” nucleon, in the spirit of the dipole picture of high-energy scattering in the BFKL model [16], and then converted the kinematical variables to those corresponding to a leading parton in proton–proton scattering. Our criterion for proximity to the black body limit (BBL) was that  $\Gamma^{\text{dipole-proton}}(s, b) > 0.5$ , which corresponds to a probability for inelastic interaction of  $> 0.75$ . Fig. 8 shows an estimate of the critical transverse momentum for leading partons with momentum fractions of the order  $x_1 \sim 10^{-1}$ , as a function of the impact parameter of the  $pp$  system [1]. Because the gluon density at  $x_2 \sim 10^{-6}$  is maximum in the transverse center of the proton, and the distribution of leading partons is likewise concentrated at small transverse distances, the chances for “black” interactions are greatest in central  $pp$  collisions (as *e.g.* those in which heavy particles are produced). This is reflected in the rapid drop of  $p_{\perp, \text{BBL}}^2$  with  $b$  in Fig. 8. One sees that  $p_{\perp, \text{BBL}} \sim$  several GeV in central collisions at LHC. Substantially smaller values are obtained at the Tevatron energy.

To determine the typical transverse momenta of leading partons in events with new particle (or hard dijet) production, we need to average the results for  $p_{\perp, \text{BBL}}^2$ , Fig. 8, over  $pp$  impact parameters, with the distribution implied by the hard production process,  $P_2(b)$ , Eq. (10) [or, in the case of four jet production, with  $P_4(b)$ , Eq. (11)]. We find that the suppression of large impact parameters implied by the hard process (*cf.* Fig. 5) is sufficient to keep  $p_{\perp, \text{BBL}}$  above 1 GeV/ $c$  in more than 99% of events at LHC. The resulting average values of  $p_{\perp, \text{BBL}}^2$  are shown in Fig. 9.

Our estimates show that in  $pp$  collisions at LHC the leading partons acquire substantial transverse momenta due to “black interactions” with the small- $x_2$  gluons in the other proton. A much weaker effect is found at the Tevatron energy. The origin of this difference is the increase in the gluon density due to the decrease of  $x_2$  between Tevatron and LHC energies, *cf.* Eq. (12). This indicates that the final state characteristics of central  $pp$  collisions at LHC will be substantially different from what one expects from the extrapolation of Tevatron results, see Section VI.

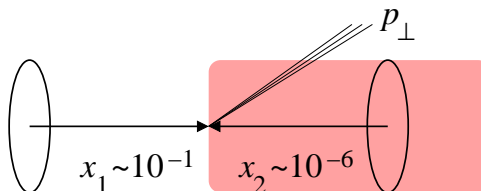


Figure 7: The black body limit in central  $pp$  collisions: Leading partons in one proton,  $x_1 \sim 10^{-1}$ , interact with a dense medium of small- $x_2$  gluons in the other proton (shaded area), acquiring a large transverse momentum,  $p_\perp$ .

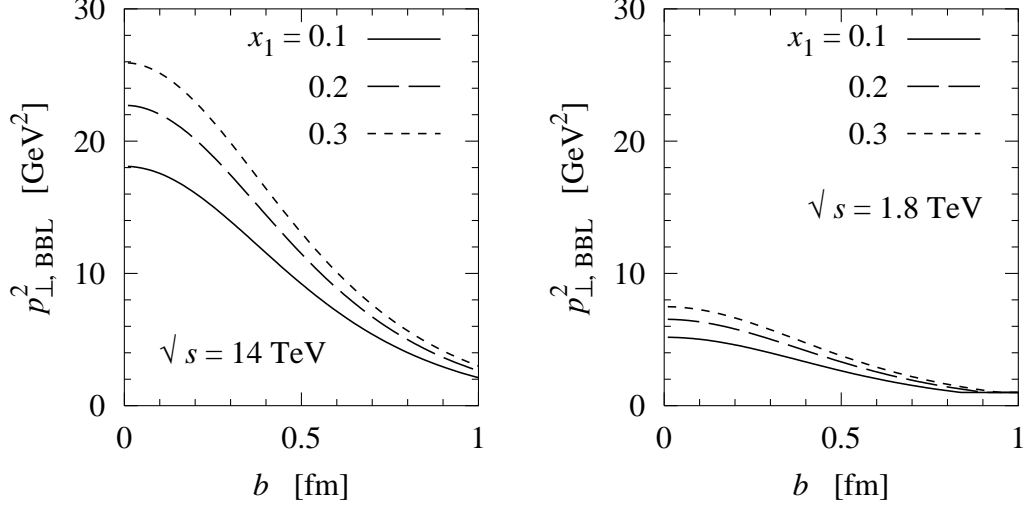


Figure 8: The critical transverse momentum squared,  $p_{\perp, \text{BBL}}^2$ , below which the interaction of a leading gluon (momentum fraction  $x_1$ ) with the other proton is close to the black body limit, as a function of the impact parameter of the  $pp$  collision,  $b$ . For leading quarks, the values of  $p_{\perp, \text{BBL}}^2$  are about half of those for gluons shown here. Shown are the estimates for LHC (left panel) and Tevatron energies (right panel).

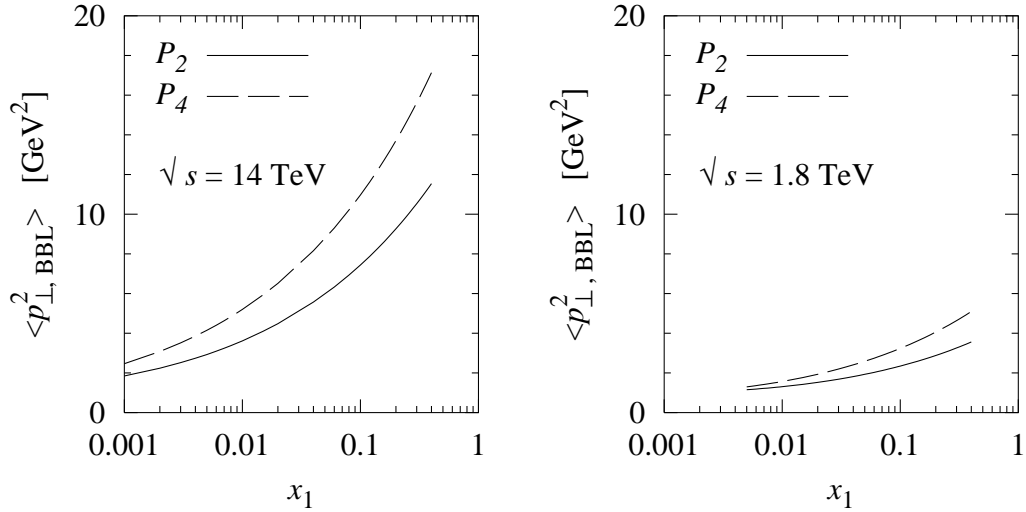


Figure 9: The average value of  $p_{\perp, \text{BBL}}^2$ , *cf.* Fig. 8, over impact parameters of the  $pp$  collision, as a function of the leading gluon's momentum fraction,  $x_1$ . The averages were computed with the impact parameter distribution corresponding to the hard dijet trigger,  $P_2$  (solid line), and the double dijet trigger,  $P_4$  (dashed line), *cf.* Fig. 6. For leading quarks, the values of  $\langle p_{\perp, \text{BBL}}^2 \rangle$  are about half of those for gluons shown here. Shown are the estimates for LHC (left panel) and Tevatron energies (right panel).

Finally, the large values of the critical transverse momentum for “black interactions” of leading partons at LHC confirm our assessment of Section III, that the probability for two nucleons at LHC energies not to interact inelastically at small impact parameters is very small.

## VI. FINAL STATE PROPERTIES IN CENTRAL $pp$ COLLISIONS

In central  $pp$  collisions the leading partons acquire large transverse momenta,  $\sim p_{\perp, \text{BBL}}$ , due to the approach to the black body limit. As a result, particle production at forward/backward rapidities will largely be dominated by incoherent parton fragmentation. One thus expects the following modifications compared to generic inelastic collisions:

- Strong suppression of leading particles, in particular nucleons (for  $z \geq 0.1$  the differential multiplicity of pions should exceed that of nucleons)
- Average transverse momenta of the leading particles  $\geq 1 \text{ GeV}/c$
- No correlations between the transverse momenta of leading hadrons (some correlations will remain, however, because two partons produced in collisions of large- $x_1$  and small- $x_2$  partons may end up at similar rapidities)
- A large fraction of events with no particles with  $z \geq 0.02 \div 0.05$  in both fragmentation regions (emergence of long-range rapidity correlations), and large energy release at rapidities  $y = 4 \div 6$ .

Another effect of the multiple scattering of large- $x_1$  partons with small- $x_2$  gluons in the other proton is the shift of a large number of small- $x_2$  gluons to larger rapidities (“holes”). This amounts to the creation of a substantial amount of color charge, and should result in an increase of soft particle multiplicities over a broad range of rapidities (albeit much smaller than if the particles originated from independent fragmentation). Such an increase should in fact be present already at Tevatron energies, in events with a trigger on two-jet or  $Z^0$  production. An increase of the multiplicity at rapidities  $|y| \leq 1.0$  was indeed observed in Ref. [17], which investigated the correlation of the underlying event structure with the presence of such a trigger. It is important to extend these studies to higher rapidities.

To summarize, in  $pp$  collisions at LHC new particles will be produced in a much more “violent” strong-interaction environment than one would expect from the extrapolation of the properties of minimum bias events at the Tevatron. Even the extrapolation of properties of hard dijet events should not be smooth, as the transverse momenta acquired by leading partons are estimated to be substantially larger at LHC than at Tevatron, see Figs. 8 and 9.

## VII. DIFFRACTIVE PROTON DISSOCIATION INTO THREE JETS

LHC will offer an opportunity to study a variety of hard diffractive processes in  $pp$  and  $pA$  scattering. One interesting aspect of such processes is that they allow to probe rare small-size configurations in the nucleon wave function.

Recently, a color transparency phenomenon was observed in the coherent dissociation of pions into two high- $p_{\perp}$  jets,  $\pi + p(A) \rightarrow \text{jet1} + \text{jet2} + p(A)$  [18], consistent with the predictions of Refs. [19, 20]. In this process the pion scatters off the target in a point-like  $q\bar{q}$  configuration. Similarly, in the proton wave function there should exist configurations consisting of only valence quarks, and having a small transverse size. A proton in such a configuration can scatter elastically off the target and fragment into three jets, corresponding to the process

$$p + p(A) \rightarrow \text{jet1} + \text{jet2} + \text{jet3} + p(A). \quad (13)$$

The cross section for the diffractive process (13) can be evaluated based on the kind of QCD factorization theorem derived in Ref. [20]. It is proportional to the square of the gluon density in the nucleon at  $x \approx M^2(3 \text{ jets})/s$ , and virtuality  $Q^2 \sim (1 \div 2)p_{\perp}^2$  [21]. The distribution over the fractions of the proton longitudinal momentum carried by the jets is proportional to the square of the light-cone wave function of the  $|qqq\rangle$  configuration, which at large transverse momenta behaves as

$$\psi_N(z_1, z_2, z_3; \mathbf{p}_{\perp 1}, \mathbf{p}_{\perp 2}, \mathbf{p}_{\perp 3}) \propto \sum_{i \neq j} \frac{\Phi_N(z_1, z_2, z_3)}{p_{\perp i}^2 p_{\perp j}^2}. \quad (14)$$

Here  $\Phi_N$  is the nucleon distribution amplitude, whose asymptotic shape is  $\Phi_N \propto z_1 z_2 z_3$ . The differential cross section is given by

$$\begin{aligned} \frac{d\sigma}{dz_1 dz_2 dz_3 d^2p_{\perp 1} d^2p_{\perp 2} d^2p_{\perp 3}} &= c_N [\alpha_s x G(x, Q^2)]^2 \frac{\Phi_N^2(z_1, z_2, z_3)}{p_{\perp 1}^4 p_{\perp 2}^4 p_{\perp 3}^4} F_g^2(x, t) \\ &\times \delta^{(2)}(\sum \mathbf{p}_{\perp i} - \mathbf{\Delta}_{\perp}) \delta(\sum z_i - 1), \end{aligned} \quad (15)$$

where  $\mathbf{\Delta}_{\perp}$  is the momentum transfer to the surviving proton ( $\Delta_{\perp}^2 = -t$ ). The coefficient  $c_N$  is calculable in QCD.  $F_g(x, t)$  denotes the two-gluon form factor of the nucleon, see Section II. A numerical estimate of the cross section

for 3-jet production at the LHC energy, with  $p_\perp$  of one of the jets larger than a given value (here: 10 GeV/c) and all other variables integrated over, gives

$$\sigma(pp \rightarrow 3\text{jets} + p) \approx \frac{[\alpha_s x G(x, Q^2)]^2}{p_\perp^8} \approx 10^{-(6 \div 7)} \left( \frac{10 \text{ GeV}}{p_\perp} \right)^8 \text{ mb.} \quad (16)$$

The probability of the  $|qqq\rangle$  configuration was estimated using a phenomenological fit to the probability of configurations of different interaction strengths in a nucleon, see Refs. [21, 22] for details. An important question is whether the cross section will grow up to the LHC energy, as was assumed in this estimate, in which the gluon density was extrapolated to values of  $x \sim 10^{-5}$ .

Experimentally, the main difficulty will be to measure jets at very high rapidities,  $y_{\text{jet}}(p_\perp = 10 \text{ GeV}/c) \sim 6$ , and with a large background from leading-twist hard diffraction. The latter will be suppressed in  $pA$  collisions, since the coherent 3-jet process has much stronger  $A$ -dependence than the background.

Finally, we note that it would be possible to study also the process  $pp \rightarrow pp + \text{two jets}$ , which is similar to pion dissociation into two jets. Experimentally, this would require the measurement of jets at rapidities  $y \sim 4$ .

### VIII. EXCLUSIVE DIFFRACTIVE HIGGS PRODUCTION

Hard diffractive processes are also being considered in connection with the production of new heavy particles in  $pp$  collisions at LHC. In particular, the exclusive diffractive production of Higgs bosons,

$$p + p \rightarrow p + (\text{gap}) + H + (\text{gap}) + p, \quad (17)$$

is regarded as a promising candidate for the Higgs search; see Ref. [3] and references therein. From the point of view of strong interactions, this process involves a delicate interplay between “hard” and “soft” interactions, which can be described within our two-scale picture of the transverse structure of the nucleon [14]. The Higgs boson is produced in a hard partonic process, involving the exchange of two hard gluons between the nucleons. The impact parameter distribution of the cross section for this process is described by the square of the convolution of the transverse spatial distributions of gluons in the in and out states,  $P_4(b)$ , defined in Eq. (11), where the scale is of the order of the gluon transverse momentum squared,  $\sim M_H^2/4$ . In addition, the soft interactions between the the spectator systems have to conspire in such a way as not to fill the rapidity gaps left open by the hard process. The probability for this to happen is approximately given by one minus the probability of an inelastic  $pp$  interaction at a given impact parameter, Eq. (6), or  $|1 - \Gamma^{pp}(s, b)|^2$ . The product of the two probabilities, which determines the  $b$ -distribution for the total process, is shown in Fig. 10. At small  $b$  the probability for no inelastic interaction is very small  $|1 - \Gamma^{pp}|^2 \approx 0$ , leading to a strong suppression of small  $b$  in the overall distribution.

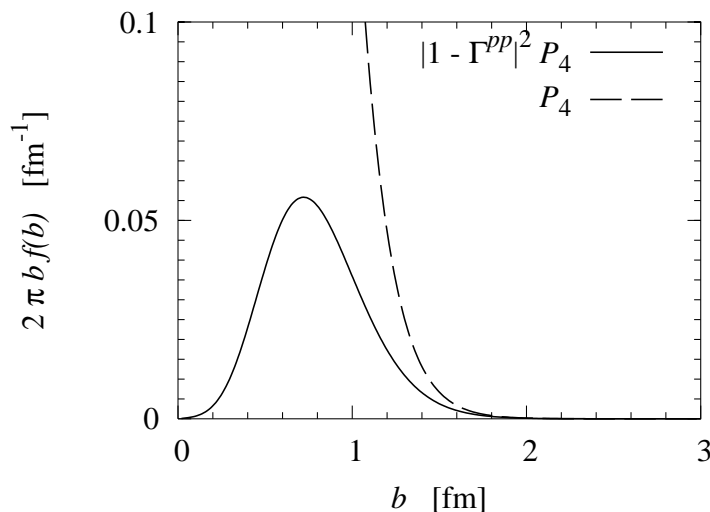


Figure 10: The impact parameter distribution of the cross section for diffractive Higgs production at LHC ( $s = 14 \text{ TeV}$ ). Dashed line:  $b$ -distribution of the hard process,  $P_4(b)$ , Eq. (11), cf. Fig. 6. Solid line:  $b$ -distribution of the total process,  $|1 - \Gamma^{pp}(s, b)|^2 P_4(b)$ . The mass parameter in the two-gluon form factor was chosen as  $m_g^2 = 1 \text{ GeV}^2$ .

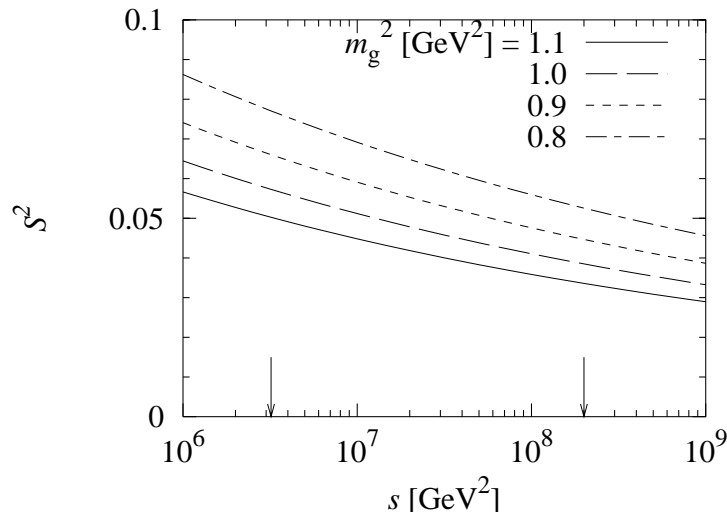


Figure 11: The rapidity gap survival probability,  $S^2$ , Eq. (18), as estimated in Ref. [14]. Shown is the result as a function of  $s$ , for various values of the mass parameter in the two-gluon form factor,  $m_g^2$ . The Tevatron and LHC energies are marked by arrows.

The so-called rapidity gap survival probability, which measures the “price” to be paid for leaving the protons intact, is given by the integral [14]

$$S^2 \equiv \int d^2b |1 - \Gamma^{pp}(s, b)|^2 P_4(b), \quad (18)$$

Fig. 11 shows our result for this quantity, with  $s$  ranging between Tevatron and LHC energies, for various values of the dipole mass in the two-gluon form factor of the nucleon,  $m_g^2$ , Eq. (3). The survival probability decreases with  $s$  because the size of the “black” region at small impact parameters (in which inelastic interactions happen with high probability) grows with the collision energy. Note that the effective  $x$  values in the gluon distribution decrease with the energy (for fixed mass of the produced Higgs boson), resulting in smaller effective values of  $m_g^2$ . This makes the actual drop of the survival probability with energy slower than appears from the fixed- $m_g^2$  curves of Fig. 11.

Our estimates of  $S^2$  are in reasonable agreement with those obtained by Khoze et al. [23] in a multi-Pomeron model, as well as with those reported by Maor et al. [24]. In view of the different theoretical input to these approaches this is very encouraging. Note that our estimate of the survival probability applies equally well to the production of two hard dijets instead of a Higgs boson.

## IX. INCLUSIVE HARD DIFFRACTIVE PROCESSES

Inclusive hard diffractive processes, such as

$$\begin{aligned} p + p &\rightarrow p + (\text{gap}) + 2 \text{ jets} + X && \text{“single diffractive”,} \\ p + p &\rightarrow p + (\text{gap}) + 2 \text{ jets} + X + (\text{gap}) + p && \text{“double diffractive”,} \end{aligned} \quad (19)$$

offer a possibility to probe the “periphery” of the proton with hard scattering processes. The cross section for these processes is again suppressed compared to the naive estimate based on the diffractive parton densities of the proton measured in  $ep$  scattering at HERA. As in the case of exclusive diffractive Higgs production, the cause of this is the very small probability for the nucleons not to interact inelastically at small impact parameters. The suppression factors can be estimated by generalizing the approach to the description of hard and soft interactions outlined in Section VIII. Simple estimates along the lines of Eq. (18) naturally reproduce the suppression factors of the order  $0.1 \div 0.2$  observed at Tevatron. However, the results in this case are more sensitive to the details of the impact parameter dependence of the hard scattering process and the soft spectator interactions.

In particular, the study of inclusive hard diffractive processes at LHC will allow to *i)* investigate how the overall increase of the nucleon size with energy leads to a suppression of hard diffraction, *ii)* check how the rate of suppression depends on the  $x$ -value of the parton involved in the hard process, *iii)* look for the breakdown of Regge factorization, that is, the change of the diffractive parton distributions with  $x_P$ .

## X. CONCLUSIONS

Interactions close to the black body limit play an important role in  $pp$  collisions at LHC energies. They largely determine the strength of the elastic  $pp$  amplitude at small impact parameters, and lead to a strong suppression of hard and soft diffractive processes. They also determine the dynamics of spectator interactions in events with new particle production, and cause substantial changes in the final state characteristics as compared to generic events. A systematic study of these effects (*e.g.* with a trigger on hard dijet production) will allow one to investigate the small- $x$  dynamics of high gluon densities in  $pp$  scattering, at densities comparable to those reached in the heavy ion collisions at LHC energies.

The final state characteristics of central collisions at LHC are predicted to be very different from the naive extrapolation of Tevatron results, where the effect of “black interactions” is much weaker.

Dedicated studies of hard diffraction at LHC, with a large acceptance in the very forward region, can provide unique information about the transverse spatial distribution of gluons in the nucleon, as well as the growth of the gluon density with energy. This information will be crucial for understanding QCD dynamics in the regime of high gluon densities, and for observing new phenomena reflecting the three-dimensional structure of the nucleon.

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